

# Improving the Prospects for Detecting Extrasolar Planets in Gravitational Microlensing Events in 2002

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## ABSTRACT

Gravitational microlensing events of high magnification have been shown to be promising targets for detecting extrasolar planets. However, only a few events of high magnification have been found using conventional survey techniques. Here we demonstrate that high magnification events can be readily found in microlensing surveys using a strategy that combines high frequency sampling of target fields with online difference imaging analysis. We present 10 microlensing events with peak magnifications greater than 40 that were detected in real-time towards the Galactic Bulge during 2001 by MOA. We show that Earth mass planets can be detected in future events such as these through intensive follow-up observations around the event peaks. We report this result with urgency as a similar number of such events are expected in 2002.

**Key words:** Gravitational lensing: microlensing—stars: planetary systems

## 1 INTRODUCTION

The importance of well-aligned or high magnification microlensing events for detecting planetary companions to the lens star was first pointed out by Griest & Safizadeh (1998). They demonstrated that Jupiter-mass planets are readily detectable (if present) in events with maximum amplification,  $A_{\max}$ , as low as 10, and that Neptune-mass planets are detectable in events with  $A_{\max} = 50$ , if they are monitored intensely around their times of peak magnification. Unfortunately, the vast majority of the more than 1000 microlensing events that have now been detected by survey groups (Alcock et al. 2000; Derue et al. 2001; Udalski et al. 2000; Bond et al. 2001a) were of low magnification. We are aware of only one event with high magnification that received intensive observational coverage at its peak. This event, MACHO 98-BLG-35, reached  $A_{\max} \sim 80$ . The observations yielded large exclusion regions for gas-giant planets surrounding the lens star, and also evidence for an Earth-mass planet near its Einstein ring (Rhie et al. 2000; Bond et al. 2001b). Two other high magnification events, OGLE 00–

BUL-12 and MACHO 99-LMC-2, received less intensive coverage yet still yielded large exclusion regions for gas-giant planets (Bond et al. 2001b). An upper limit of the order of 30% on the abundance of Jupiter-like planets has also been obtained by the PLANET collaboration from a study of typical microlensing events (Albrow et al. 2001; Gaudi et al. 2002). This study included the event MACHO 98-BLG-35 in which they excluded Jovian planets but were unable to draw any conclusions on the presence of terrestrial planets. This is not inconsistent with the conclusions of Bond et al (2001b) since the PLANET coverage of the peak of this event was less intensive and the data were analysed using a procedure that is generally less accurate.

Significant progress could clearly be made if one had a larger sample of high magnification events to work with. The purpose of this letter is to report the detection of 10 high magnification events thereby demonstrating that high magnification events can be detected with high efficiency, and to urge follow-up observations of future events.

## 2 OBSERVATIONS

During 2000–2001 a campaign of observations was undertaken by the MOA collaboration with the aim of improving the detection rate of high magnification events. A 0.6m telescope at the Mt John Observatory in New Zealand ( $170^\circ$  E,  $44^\circ$  S) with a mosaic camera comprised of three  $2k \times 4k$  thinned CCDs was used. An area  $17 \text{ deg}^2$  towards the Galactic Bulge that is relatively unobscured by dust was monitored.

The MOA microlensing search procedure involves a combination of multiple observations (up to six times) per night and real-time difference imaging to pick up microlensing events. Images taken during the pilot year of 2000 were used to build a database of variable stars and to detect some microlensing events (Bond et al. 2001a). The observations in 2001 were made primarily to search for microlensing events and to provide real-time alerts<sup>1</sup> to follow-up groups. A total of 53 possible microlensing events were detected in real time in 2001, of which 10 had  $A_{\max} > 40$ . The details of these events are given in Table 1 and their light curves are shown in Fig. 1. Most of the events had  $A_{\max} \geq 100$  and all stood out clearly as shown, for example, in Fig. 2.

We determined the parameters  $A_{\max}$  and the the Einstein crossing time  $t_E$  by fitting the standard single lens microlensing profile given by Paczynski (1986). The constraints on these parameters were determined by a thorough examination over a range of values of  $A_{\max}$  and  $t_E$ . For some events only lower limits could be determined. The large uncertainty in  $A_{\max}$  for some of the events in Table 1 was mainly due to the less than complete coverage of the peak of their profiles. The intrinsic faintnesses of the sources also contributed to the uncertainties. With the exception of the first event, all events shown in Table 1 had faint baseline intensities at or below the detection threshold. However, since difference imaging was used, the photometry and subsequent derivation of event parameters was unaffected by blending and thus free from systematic effects that may result using conventional profile fitting photometry techniques (Alcock et al. 2000; Wozniak 2000; Bond et al. 2001a)

The MOA strategy of nightly multiple observations of survey fields is different from that of earlier survey projects (Alcock et al. 2000; Udalski et al. 2000; Derue et al. 2001). It is noteworthy that most of the events shown in Table 1 and Fig. 1 were observable only for a few days near their peaks. Events 32, 37, 41, 46, and 50 were especially rapid with most of the brightness changes occurring in just one night. Such events had not been seen in previous surveys. If we had adopted the strategy of just a single observation of the survey fields per night, only events 2, 5, and possibly 7 would have been picked up. The multiple nightly sampling strategy would therefore appear to give 3–5 fold increase in the detection efficiency for rapid events.

Our use of difference imaging analysis has permitted the detection of events that would have otherwise been missed due to some combination of intrinsic faintness of the source and the degree of image crowding. Previous offline analyses using difference imaging have been carried out on the image databases produced by MACHO (Alcock et al. 2000) and

OGLE (Wozniak 2000) and have also shown that microlensing events with faint source stars can be detected. However, the sampling rate over the target fields in these surveys was only of the order of once per night and events like the rapid ones presented appear to have been missed.

Our survey procedure also differs from previous ones in that the difference imaging analysis is carried out on-line. This crucial feature enables events to be alerted to other observatories in real-time for follow-up. Without this, the potential for planet detection described in the following section could not be realized. The real-time feature of our procedure was also a factor in the scheduling of our survey fields. For some of the events shown in Fig. 1, the observation frequency of those fields containing the events was increased following the event alert. Unfortunately, bad weather and interruptions due to daylight prevented us from obtaining complete coverage of their peaks.

In general, the MOA survey procedure, which combines multiple observations of each of the survey fields nightly with on-line difference imaging analysis, evidently allowed us to tap into a huge reservoir of faint microlensing sources that had previously not been fully utilized. Our procedure enables detection of these events with small telescopes during the brief time when they are highly magnified, i.e. when the lens and the source are well-aligned. The fitted Einstein crossing times,  $t_E$ , for these events are not, however, unusually short. The crossing time for an event depends upon the mass of the lens and the transverse velocity of the lens with respect to source, and these parameters are not significantly biased by our detection procedure. With the exception of event 5, which has an unusually long duration of  $\sim 200$  days<sup>2</sup>, all events had  $t_E$  in the range 10–40 days, consistent with the distribution found using the conventional survey technique (Udalski et al. 2000). Thus we see no evidence that the MOA survey probes a different population of lens stars from that in previous surveys. However, it does probe a different population of source stars. The data in Table 1 imply the source stars for all the events except the first are sun-like when allowance is made for reddening caused by dust (Schlegel, Finkbeiner, & Davis 1998). These dwarf stars are ideal for planet hunting because source-size effects that tend to wash out planetary signals are minimised (Griest & Safizadeh 1998).

## 3 DISCUSSION

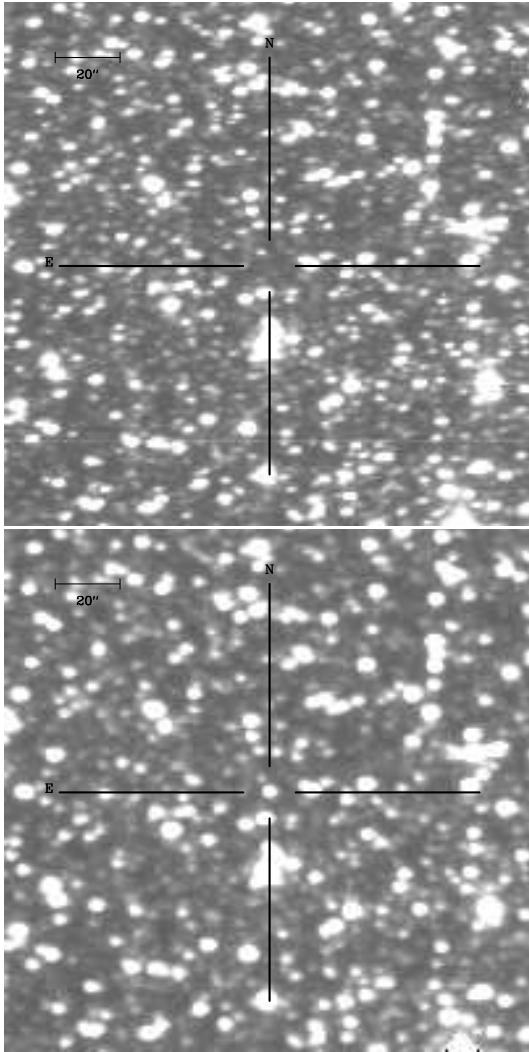
It is evident from the above that microlensing events of high magnification with solar-type sources can be readily detected. Griest & Safizadeh (1998) considered the detection of planets with masses ranging from that of Neptune up to that of Jupiter in microlensing events with  $A_{\max}$  up to 50. We have considered the detectability of lower mass planets in events with  $A_{\max} \geq 50$  such as those reported here. It is beyond the scope of this letter to consider in depth, the range of sampling rates, detection criteria, telescopes, etc, that could be used when monitoring high magnification

<sup>1</sup> <http://www.phys.canterbury.ac.nz/~physib/alert/alert.html>

<sup>2</sup> Six similarly long timescale events with  $t_E > 200$  days have been previously detected in the MACHO survey. These may be due to microlensing by stellar mass black holes (Bennett et al. 2001)

**Table 1.** Details of high magnification events detected in 2001.

Event	R.A.	Dec.	$I_{\max}$	$A_{\max}$	$t_E$ (days)	$t_{\text{FWHM}}$ (hours)
2	17 55 09.1	-28 44 59.4	11.6	$42.6 \pm 1.1$	$38.2 \pm 0.7$	74.6
5	18 16 42.9	-23 24 19.6	14.3	$200 \pm 124$	$194 \pm 17$	80.7
7	18 08 58.8	-27 36 11.9	14.6	$56 \pm 17$	$22.0 \pm 5.8$	32.7
16	18 11 50.8	-27 33 28.6	<14.1	>73	$28.6 \pm 3.8$	<32.6
20	18 06 50.7	-27 15 13.3	16.2	$70 \pm 326$	$14.9 \pm 64.5$	17.7
32	18 03 35.2	-29 52 20.8	<14.1	>96	$17.6 \pm 11.5$	<15.3
37	17 55 23.4	-28 56 44.2	<14.5	>186	>23.8	~10.6
41	18 07 13.4	-25 25 18.3	<14.5	>137	>20.6	~12.5
46	17 57 48.9	-29 36 35.5	14.6	$156 \pm 320$	$16.9 \pm 33.5$	9.1
50	17 56 33.0	-28 54 19.5	<14.2	>289	>31.7	~9.1

**Figure 2.** Sample images of event MOA 01-BLG-5 taken when the event was at its baseline (top) and near its peak (bottom). The event stood out clearly near its peak, but was invisible with the MOA telescope at its baseline.

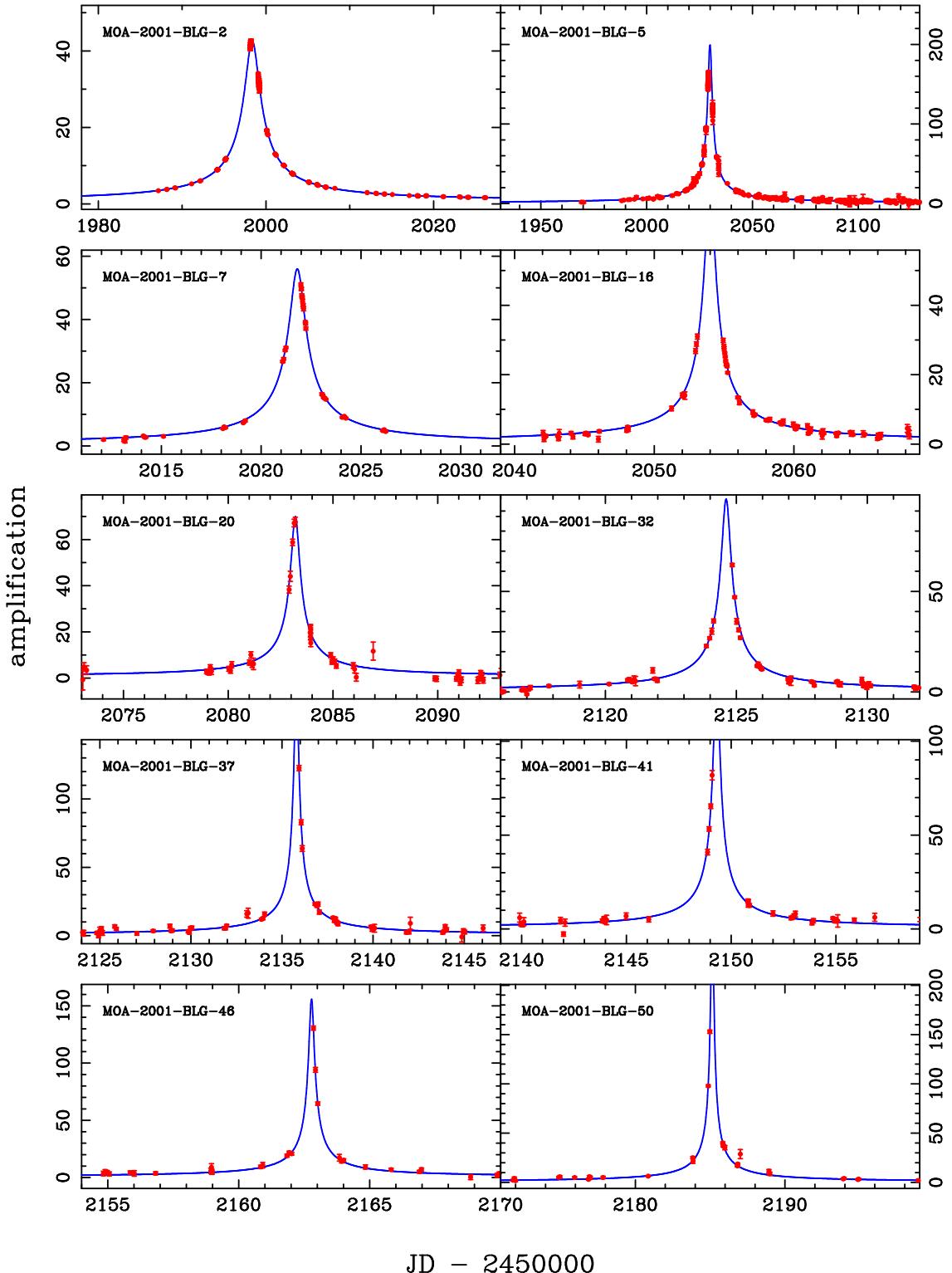
events. We present here some calculations as a benchmark as to what could be achievable in future events similar to those presented here.

We simulated events with  $A_{\max}$  of 50, 100, and 200 that reached a peak I magnitude of 15. We assumed

they were monitored intensively during the time interval  $[-0.5t_{\text{FWHM}}, 0.5t_{\text{FWHM}}]$  where  $t_{\text{FWHM}}$  is the full-width at half-maximum of the microlensing light curve. This is given by  $t_{\text{FWHM}} = 3.5t_E/A_{\max}$  and is typically in the range 10–30 hours. We assumed 300 measurements were made in this time interval with accuracy two times worse than the photon statistical limit achievable with a 1-m class telescope, consistent with accuracies attained using the difference imaging technique. Full details of these simulations are reported elsewhere (Rattenbury et al 2002, submitted to MNRAS). Simulated light curves corresponding to a range of planetary positions were generated and the quantity  $\Delta\chi^2 = \chi^2_{\text{single}} - 300$  was calculated for each light curve. Here,  $\chi^2_{\text{single}}$  denotes the value derived by fitting the light curve for a single, planetless lens to the simulated data for a lens with a planet. We adopted a detection criterion of  $\Delta\chi^2 > 60$  corresponding to a <1% probability for statistical fluctuations causing a planet-like signal.

Fig. 3 shows the zones of detectability for an Earth-mass planet under the above conditions. It is seen that Earth-mass planets can be detected with high efficiency if their orbital radii projected onto the lens plane lies within the range 0.7–1.5 $r_E$  or  $\sim$ 1.3–2.9 AU in high magnification events that are monitored intensely during  $t_{\text{FWHM}}$ . For larger planets heavier than Neptune, the zones of detectability extend far beyond the region around the Einstein ring especially when  $A_{\max} \geq 100$ . Jupiter-mass planets are detectable almost anywhere in these events.

During the 2002 southern winter viewing season, we expect to detect around 10 high magnification microlensing events in real-time. We propose that these events be monitored with a sampling as dense as possible during the time interval given by  $t_{\text{FWHM}}$  for the event. Given the rapid nature of many of these events, follow-up observations will need to commence within 0–24 hours following the event alert. For events with  $t_{\text{FWHM}} \sim 24$  hours, a world-wide network of 1-m class telescopes is required to carry out the peak measurements. For more rapid events, fewer telescopes are required, but a commensurate increase in telescope aperture up to 2-m is required to achieve the sensitivity shown in Fig. 3. Difference imaging should be applied to all observations so as to achieve photometry with uncertainties approaching that given by the photon noise and free from systematic effects caused by blending of the source star with neighbouring stars. Looking further ahead, continuous monitoring of the peaks of high magnification events could be car-

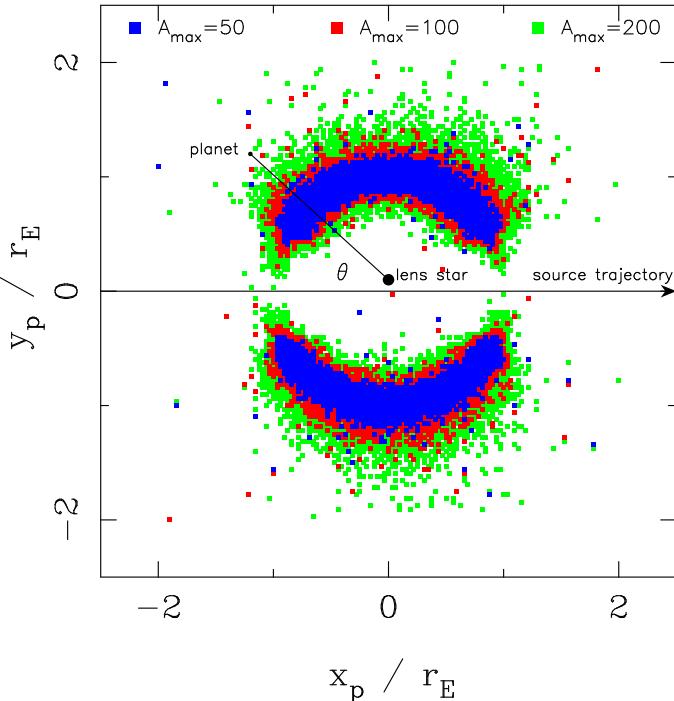


**Figure 1.** Light curves of high magnification microlensing events detected by MOA during 2001. The photometric flux measurements have been converted to amplifications using the fitted microlensing parameters given in Table 1.

ried by follow-up observations from facilities in the Antarctic or in space.

Follow-up measurements using ground or space based facilities with deep imaging capability would be required for all events in order to determine accurately the

baseline intensity of the source star. This information is required in order to determine the value of  $A_{\max}$  accurately and hence the planet:star mass ratio for any detected planet. In the case of non-detections, an accurate value of  $A_{\max}$  is required for the calculation of planetary exclusion regions.



**Figure 3.** Detectability zones in the lens plane for an Earth-mass planet orbiting a  $0.3M_{\odot}$  star in microlensing events with peak magnifications of 50, 100, and 200. The units for both axes are in  $r_E$  which is typically  $\sim 1.9$  AU. In this coordinate system, the lens star is located at position  $(0, u_0)$ , where  $u_0$  is the impact parameter, which is  $\sim 1/A_{\max}$ . The vertical position of the lens star is exaggerated in the figure. If the projected position of the planet falls in the shaded regions at the time of the microlensing event, then it is detectable at the 99% confidence level if intensive photometric monitoring of the microlensing event is carried out during the time interval  $t_{\text{FWHM}}$ . The angular diameter of the zone of detectability is  $<1$  mas.

We note that these deep follow-up observations are not time-critical and can be performed at any time after the events. Further follow-up measurements a few years later with the Next Generation Space Telescope should enable the lens star in any event to be observed directly as it begins to diverge from the source star. This would enable the absolute value of the mass of a planet to be determined, and also its absolute instantaneous projected radius at the time of the microlensing event.

#### 4 SUMMARY

We have demonstrated that high magnification microlensing events can be readily detected in microlensing surveys with a strategy of high frequency sampling of survey fields and real-time difference imaging analysis. We have presented 10 events with  $A_{\max} \geq 40$  that were detected by the MOA microlensing survey during 2001. The purpose of this letter is to bring this capability to the attention of the microlensing community. We encourage intensive follow-up observations of future high magnification events detected by MOA and similar experiments.

Microlensing probes distant planets and is thus complementary to the radial velocity and transit techniques. Ulti-

mately, a future space-based mission such as GEST (Bennett et al. 2002), dedicated to observing thousands of microlensing events will be required in order to detect substantial numbers of low mass planets (including those with masses as low as that of Mars). In the meantime however, it would appear that intensive observations of high magnification events would provide the best chances of detecting extra-solar planets in microlensing events observed from the ground.

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